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THIRD QUARTERLY PROGRESS REPORT
CONTRACT NAS 5-9178

STUDY AND ANALYSIS OF SATELLITE POWER SYSTEMS CONFIGURATIONS FOR MAXIMUM UTILIZATION OF POWER

Period Covered:

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Prepared For:

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1. INTRODUCTION

This is the Third Quarterly Progress Report covering work performed by TRW Systems under Contract NAS 5-9178, "Study and Analysis of Satellite Power Systems Configurations for Maximum Utilization of Power." This report covers the period 19 November 1965 through 18 February 1966. The study consists of six major tasks:

Task I. A survey of the power requirements of spaceborne equipment in typical unmanned satellites.

Task II. A survey of typical spacecraft electrical power system designs.

Task III. Collection and presentation of parametric data on the individual assemblies constituting a power system; (i.e., power control, energy storage, and power conditioning equipment).

Task IV. Analysis of three typical space missions, selected by GSFC, with respect to their electrical power requirements and to the characteristics of photovoltaic power systems which could meet those requirements. Various power system configurations will be evaluated with respect to efficiency, weight, reliability, and interface constraints.

Task V. Investigation of possible means of standardizing electrical power requirements for satellites as well as design of power systems and their equipments.

Task VI. Investigation of the characteristics of alternate electrical power systems using radioisotope thermoelectric generators (RTG) rather than photovoltaic sources.

The results of the first four tasks are to be used to establish an evaluation technique or method which will allow various proposed power system designs to be evaluated for optimization. Application of this technique is to be demonstrated on the designs for the three missions specified by GSFC. The identification of power systems optimized for maximum utilization of power should allow recommendations to be made for standardization of satellite power systems, requirements, and equipments.

2. PRESENT STATUS OF THE STUDY

At the conclusion of the third quarter, the planned program was approximately 70 percent complete. To date, the major portion of the effort has been devoted to the first four tasks. The present status of the work scheduled under each task is as follows:

Task I. Complete - All available additional data regarding experiment power requirements has been obtained.

Task II. Complete - Results presented in second quarterly report.

Task III. Complete - Major portion of the results presented in second quarterly report; the balance of the effort to date is reported here.

Task IV. Approximately 30 percent complete - A method of optimization evaluation has been synthesized and is described in this report. The analysis of the specified missions will be completed during the fourth quarter.

Task V. Approximately 10 percent complete - General standardization guidelines have evolved from the work performed in Tasks I - IV. These guidelines will be formalized and expanded during the fourth quarter.

Major emphasis will be placed on completing Tasks IV and V during the fourth quarter. The "Comparative Analysis Optimization" technique developed under Task IV will be assessed for applicability to the RTG system design effort of Task VI. Figure 1 is a revised program schedule updated to reflect the present status of the study.

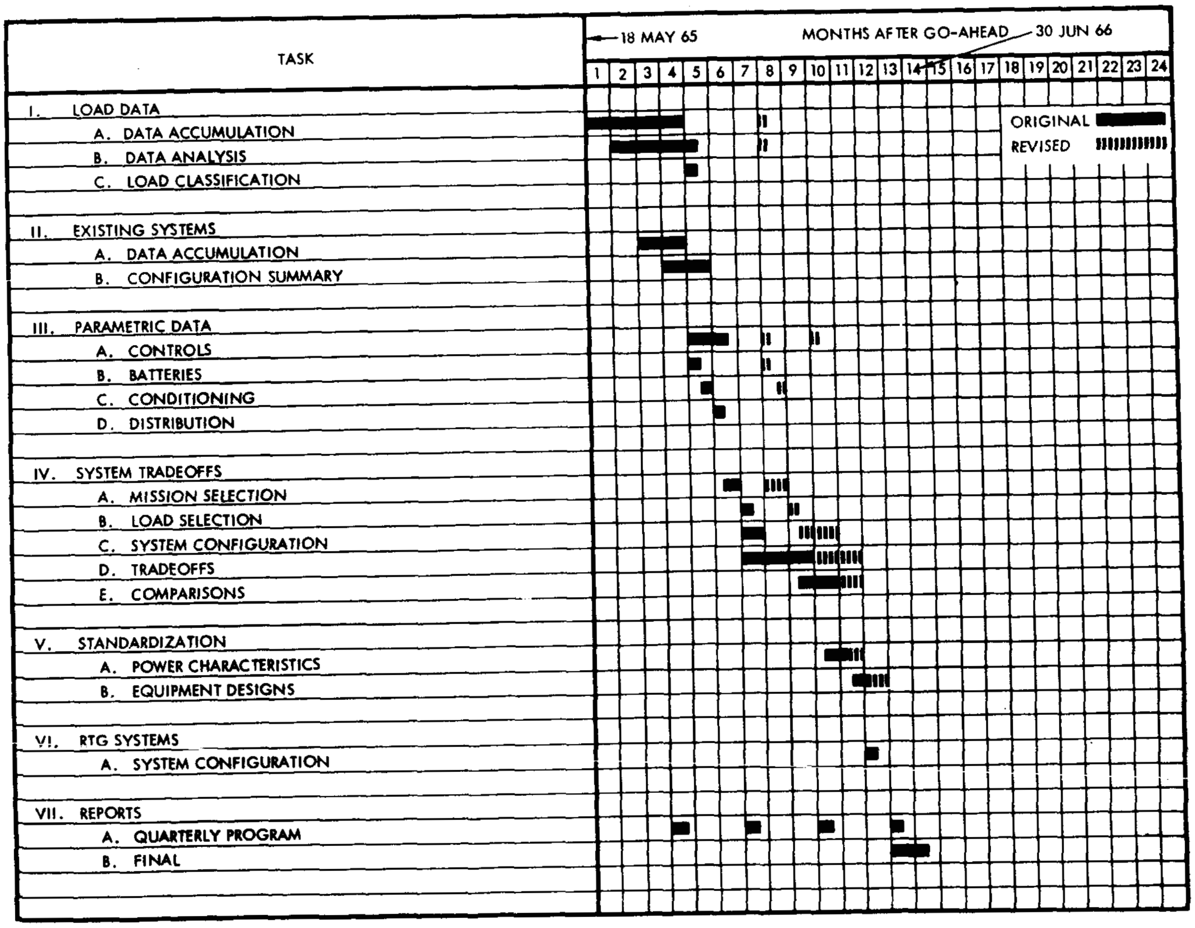

Figure 1. Revised Program Schedule

3. THIRD QUARTER STUDY RESULTS

3.1 PARAMETRIC DATA

The converter parametric data presented in the Second Quarterly Report have been expanded so that the efficiency and weight performance of the individual sections, i.e., the pre-regulator, inverter, and transformer-rectifier (TR), can be identified separately. This will allow trade-offs to be made between a single converter which provides the functions of a regulator, inverter, and TR units, and discrete equipment, such as a regulator, inverter, and TR units.

The various types of regulators and their parametric data (described in the Second Quarterly Report) have been reviewed for the specific application of battery charge or discharge control. The regulators are fundamentally the same as before except limit control functions have been added for proper battery protection. The charge and discharge voltage, temperature, and current limits are determined for each type of battery from the parametric data.

Several questions have arisen concerning the dc to dc converter parametric data presented in Figure 29, page 57, of the Second Quarterly Report. To clarify the usefulness and applicability of these data, the power, frequency, weight, and efficiency of existing dc to dc converter hardware were compared with the data presented in Figure 29. Table I lists the design criteria from which the curves in Figure 29 were derived. The existing hardware designs were adjusted to the same criteria by using the efficiency correction factor presented in Figure 31 of the Second Quarterly Report. Exhibits 1 and 2 of this report are reproductions of Figure 29 and 31, respectively, of the Second Quarterly Report.

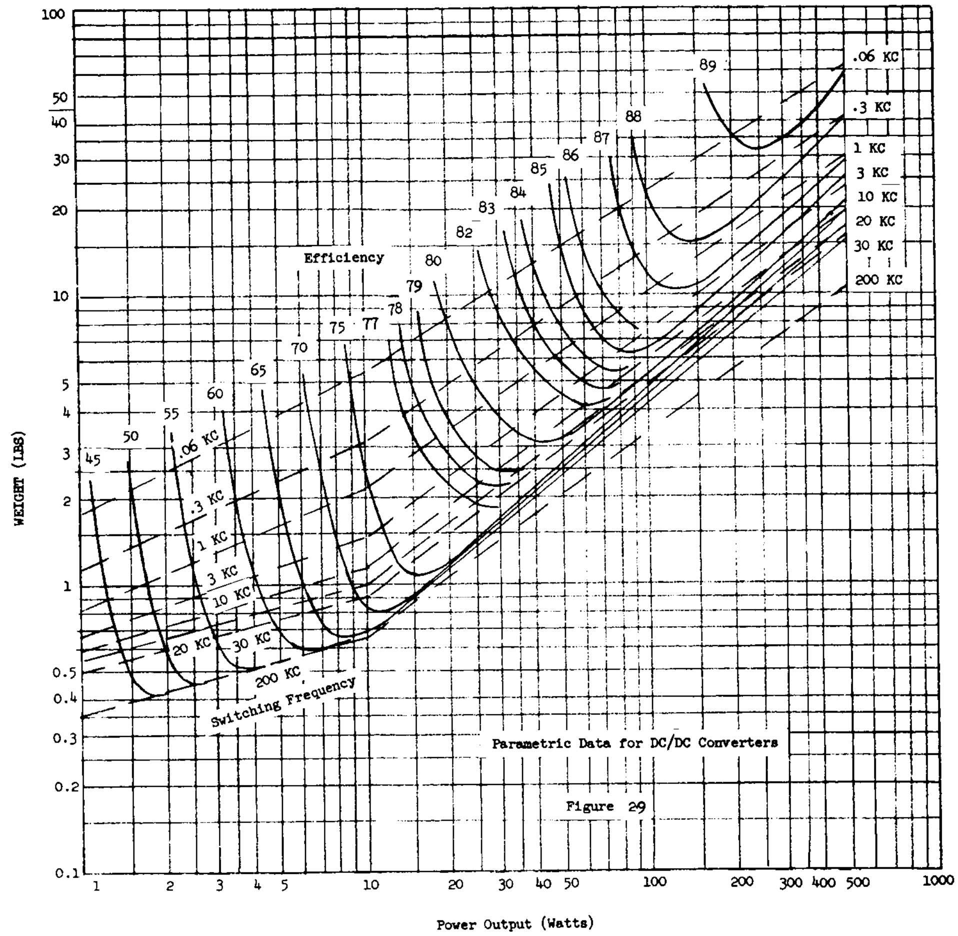

Exhibit 1

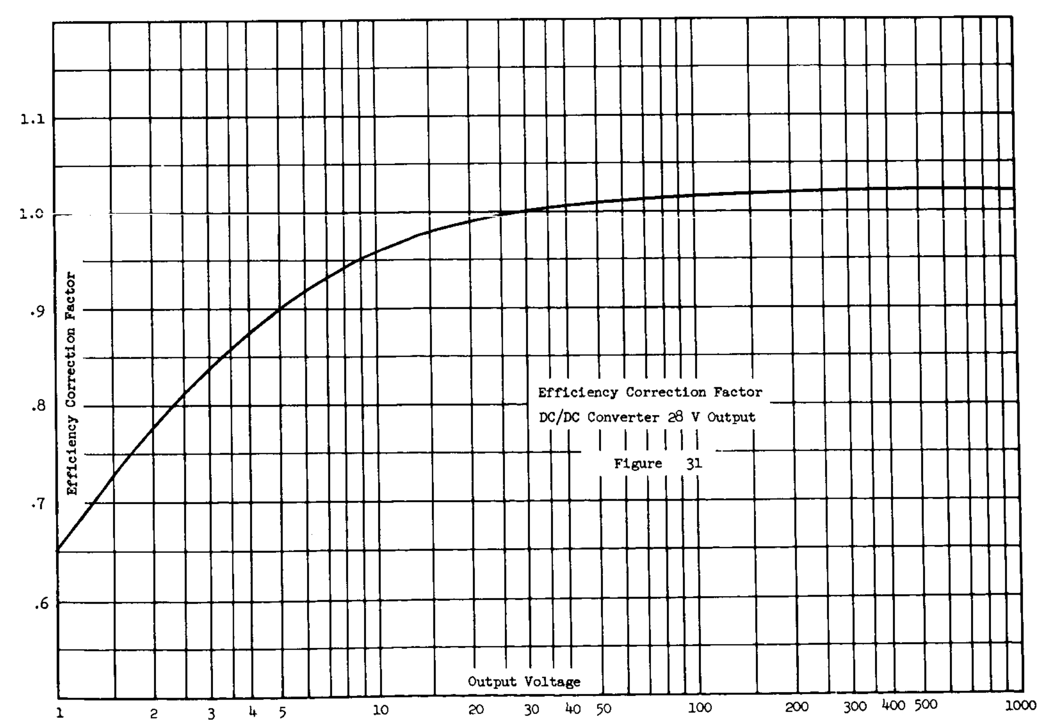

Exhibit 2

Table I. Design Criteria

Converter Type:	Pre-regulator dc to dc
Input Voltage:	28 ± 15% vdc
Single Output Voltage:	28 ± 2% vdc
Ripple and Noise:	± 1%
Overload Protection:	Current limiting
Temperature:	0-50°C
Redundancy:	None

The information presented in Figure 29 was intended to show the change in direction and relative magnitude of the various parameters. It is expected that these parameters will vary somewhat because of the many variables affecting the designs. The data compare favorably at the lower power levels. Because high power level hardware (200 to 500 w) is practically non-existent, a comparison of the data extrapolation cannot readily be verified at this time. Table II presents a comparison of the hardware data points with the curves in Figure 29.

3.1.1 Derivation of Converter Parametric Data

The general equation for the converter efficiency parameter shown in Figure 29 is:

$$\eta_o = \frac{P_o}{P_o + (P_f)_o + (P_s)_o + (P_m)_o} \tag{1}$$

where

P_o = Power output

η_o = Converter efficiency at given (P_o) and (f_o)

$(P_f)_o$ = Fixed losses at a given power output

$(P_s)_o$ = Semiconductor component losses

$(P_m)_o$ = Magnetic component losses

Converter efficiency (η_1) at a given (P_o) and a new (f_1) is:

$$\eta_1 = \frac{P_o}{P_o + (P_f)_o + (P_s)_1 + (P_m)_1} \tag{2}$$

Table II. Comparison of Parametric Data and Hardware Designs

CONVERTER DESIGN	OUTPUT VOLTAGE	POWER (W)		EFFICIENCY (%)		FREQUENCY (KC)		WEIGHT (#)	
		ACTUAL	GRAPH	ACTUAL	GRAPH	ACTUAL	GRAPH	ACTUAL	GRAPH
1	+28, +15, -28 vdc	34.64	35	78	79.5	10	10	3.0	2.8
2	+4.2 vdc	15	15	77.5* 68	76	10	10	1.45	1.50
3	+4.2 vdc	5	5	71* 63	62	10	10	1.10	0.93
4	+12.6, +6.6, -3.6, -6.0, +15, -15 vdc	2.75	2.75	57.2* 55	55	10	10	1.45	0.8
5	+12.8, +16.7, +16.0, +10.0, +15, -12.4, -16.0, +10 vdc; 15 vac	9.00	9.0	68.5* 66.4	72	6.5	6.5	3.2	1.3
6	-940, -545, +80 vdc; 4.875 vac	26	26	78.5* 80	78.5	6.5	6.5	2.35	2.5
7	+6.5, -6.65 vdc	13.99	14	71* 66	76	3.3	3.3	3.0	1.7
8	+23, +70 vdc	21.60	21.6	75.5* 74	77	3.3	3.3	2.8	2.2
9	+16, +10, -6.2, -16.1 vdc	1.91	1.91	36* 34	52	3.3	3.3	0.6	0.84
10	+28, +12.2, +10, -6.2 vdc	3.69	3.69	42* 40	57	3.3	3.3	1.1	1.0
11	+23, +70 vdc	26	26	70	79	2.4	2.4	2.2	2.8
12	+23, +70 vdc	22.1	22.1	69	78	2.4	2.4	2.2	2.5

NOTE: * - Efficiency corrected for +28 vdc single output

$$\eta_1 = \frac{1}{1 + \frac{(P_f)_o}{P_o} + \left[\frac{1}{\eta_o} - \frac{(P_f)_o}{P_o} - 1\right]\left[0.6 + 0.15\left(\frac{f_1}{f_o}\right) + 0.25\left(\frac{f_1}{f_o}\right)^{0.1}\right]} \tag{3}$$

$$W_o = X_o + Y_o + Z_o \tag{4}$$

where

W_o = converter weight for output of (P_o) at (f_o)

X_o = $W_o/3$ = weight of electronic components

Y_o = $W_o/3$ = weight of magnetic components

Z_o = $(X_o + Y_o)/2$ = weight of chassis and misscellaneous hardware

The new converter weight (W_1) for output of (P_o) at (f_1) is:

$$W_1 = X_o + Y_o\left(\frac{f_o}{f_1}\right)^{0.4} + 1/2\left[X_o + Y_o\left(\frac{f_o}{f_1}\right)^{0.4}\right]$$

$$W_1 = \frac{W_o}{2}\left[1 + \left(\frac{f_o}{f_1}\right)^{0.4}\right] \tag{5}$$

The equation relating weight to output power at a constant frequency is

$$W_i = W_o\left[\frac{P_i}{P_o}\right]^K \tag{6}$$

The factor (K) varies with frequency and the W_o used. Table III provides the approximate values for K in the area of interest.

The cross plots of weight vs power output and frequency vs power output are shown in Figure 2 for the same design centers used in Figure 29. The curves of Figure 3 relate the variation of the fixed losses $(P_f)_o$ with output power and the resulting efficiency (η_o) given by Equation (1).

Table III. K Factors versus Switching Frequency for Converters

FREQUENCY (KC)	$P_1 > 10W$; $P_0 = 10W$		$P_1 < 10W$; $P_0 = 1W$	
	K	W_0 (lb)	K_1	$(W_0)_1$ (lb)
.06	.645	5.2	.46	1.8
.3	.666	3.0	.40	1.2
1.0	.676	2.1	.40	0.82
3.0	.670	1.5	.35	0.67
10.0	.700	1.2	.30	0.6
20.0	.715	1.0	.26	0.55
30.0	.745	0.9	.255	0.5
200.0	----	----	.270	0.35

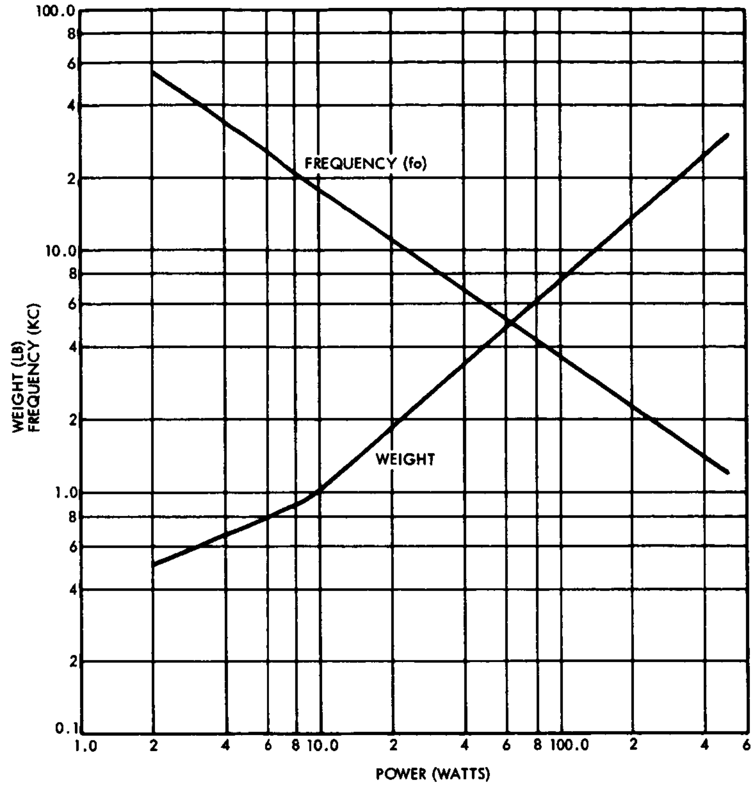

Figure 2. Design Center Parameters for Converters

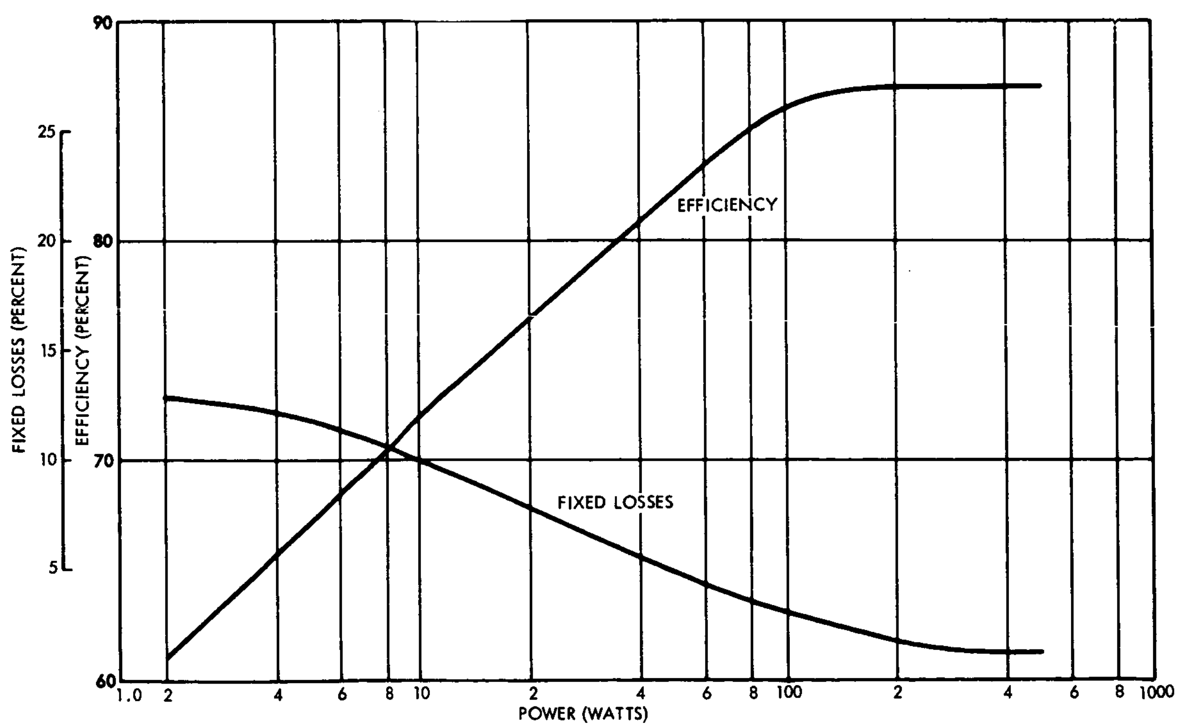

Figure 3. Design Center Efficiencies for Converters

The complete curves of Figure 29 were generated by taking the performance data of an existing converter as a design center. From this design center, the variation of efficiency (η_o) and weight (W_o) at a constant power were extrapolated using the relationships given by Figures 2 and 3. Other design centers were similarly used for different power outputs.

When the inverter function provided by a converter is considered as a separate piece of equipment, similar equations result such as the following:

$$W_j = \frac{W_m}{3}\left[1 + 2\left(\frac{f_m}{f_j}\right)^{0.4}\right] \qquad (7)$$

$$\eta_j = \frac{1}{1 + \left[\frac{1}{\eta_m} - 1\right]\left[0.6 + 0.15\left(\frac{f_j}{f_m}\right) + 0.25\left(\frac{f_j}{f_m}\right)^{0.1}\right]} \qquad (8)$$

The composite parametric curves for inverter designs, shown in Figure 4, were generated from design centers as were the converter data. Figure 5 provides the design center parameters used in conjunction with Equations (7) and (8) to generate Figure 4.

The transformer-rectifier (TR) function of the converter can also be considered as a separate entity. The following equations relate efficiency (η_h), weight (W_h) and operating frequency (f_h).

$$W_h = \frac{W_n}{16}\left[1 + 15\left(\frac{f_n}{f_h}\right)^{0.4}\right] \qquad (9)$$

$$\eta_h = \frac{1}{1 + \left[\frac{1}{\eta_n} - 1\right]\left[0.6 + 0.0667\left(\frac{f_h}{f_n}\right) + 0.333\left(\frac{f_h}{f_n}\right)^{0.1}\right]} \qquad (10)$$

Figures 6 and 7 present the parametric design curves and design center parameters for the TR designs.

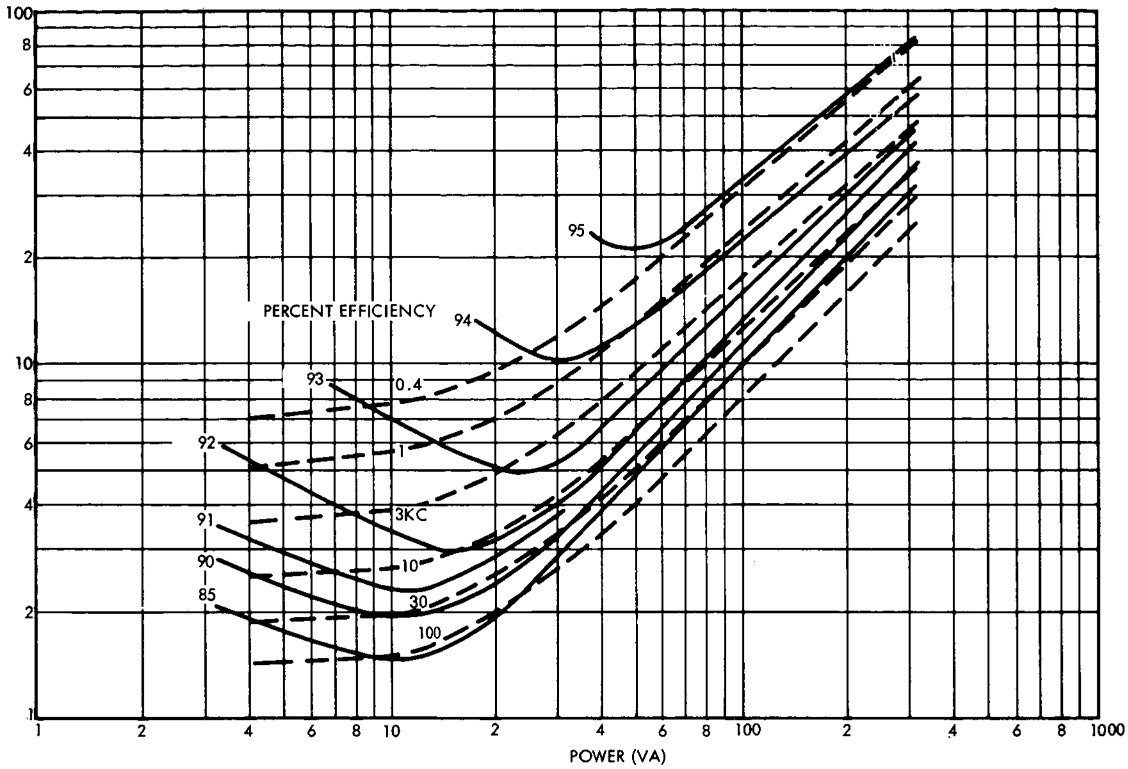

Figure 4. Unregulated Square Wave Output, Inverters

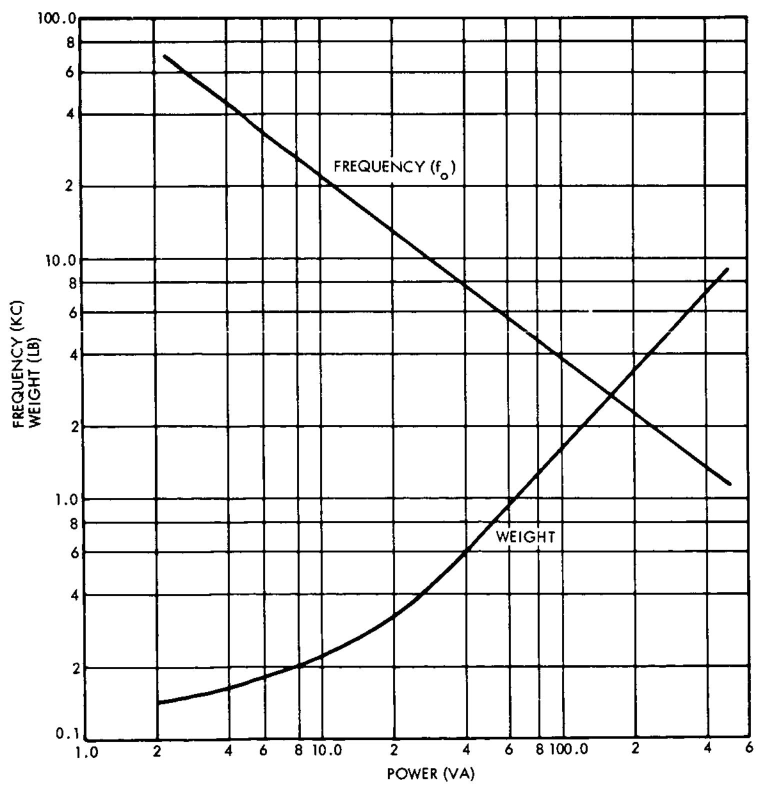

Figure 5. Design Center Parameters for Inverters

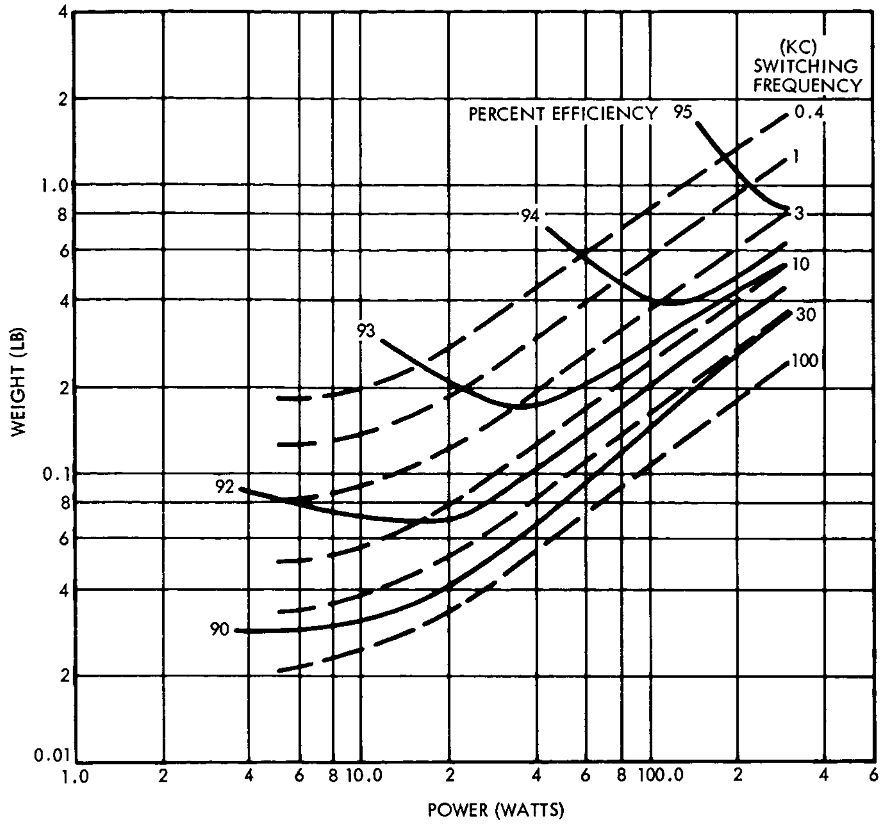

Figure 6. Data for TR Units

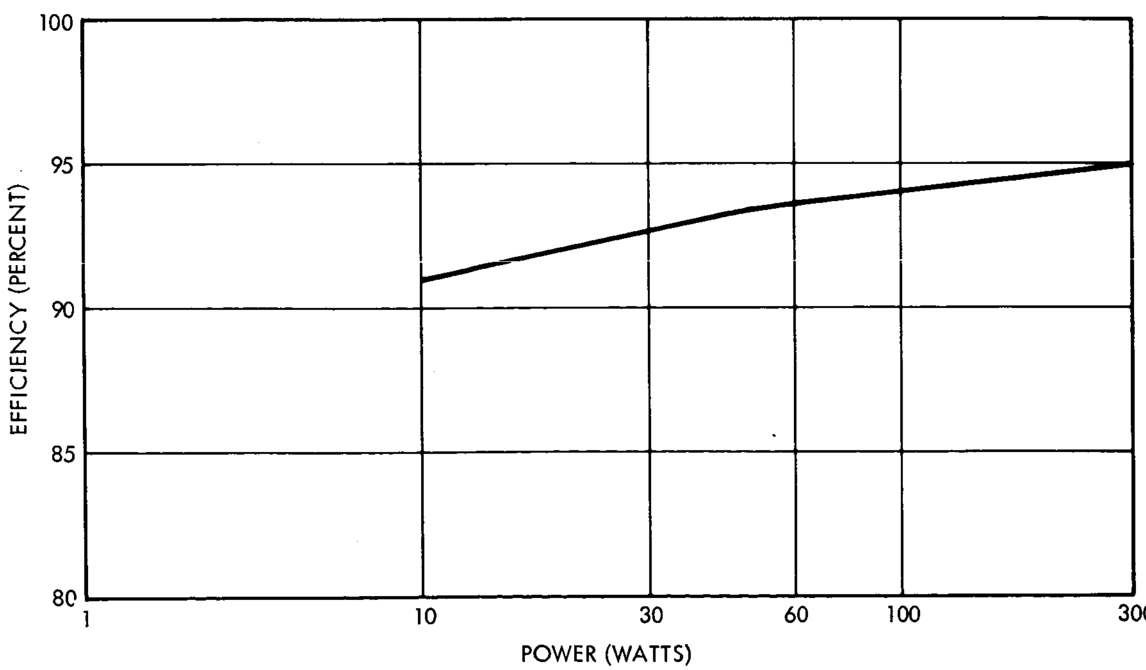

Figure 7. Design Center Efficiencies for TR Units

3.2 ANALYSIS OF LOADS

Previously, specific loads were related to major subsystems. In order to identify the more significant load parameters affecting the optimization criteria, an analysis of the parametric data was necessary. Scatter diagrams, based on flight hardware designs, were made for output power vs efficiency, output voltage vs efficiency, output voltage regulation vs efficiency, etc. It was determined that both output power and voltage had the more significant effect upon efficiency and weight. A review of the parametric design data shows that system efficiency has the following functional relationship with power:

$$\eta = f\left[b\left(1 - e^{-k\Delta_i}\right)a\right] \tag{11}$$

where

η = total efficiency of power system less prime energy generator and storage

Δ_i = percentage of total output power per output circuit.

a, b, k = constants for the particular type of conditioning equipment and operating voltages.

At a constant power output, system efficiency increases with an increase in output voltage. This increase will be modified if the ratio of the regulator input-output voltages differs significantly from unity. The relationship of system efficiency to output voltage is also exponential, but much shallower than for power output. Percent regulation and the number of voltage outputs affect efficiency, but are noticeable only when the output power and voltages are held constant. Although trends can be shown for these parameters, the available data sample is too small to establish accurate magnitudes for tradeoff purposes. Engineering judgement will be necessary in applying the trends as guidelines for these parameters in the few cases affected.

Equipment weights are similiarly related to output power and voltage for conventional designs. Extremely low weight designs are possible in special cases where efficiency, lifetime, and reliability can be sacrificed. These special cases are not included in this study.

The proportional increase of weight with output power is offset by the simultaneous increase in efficiency. Thus, it is possible to trade off weight and efficiency at any given power level.

3.3 MISSION SELECTION

The three missions specified by NASA/GSFC are typical for existing and future earth orbiting vehicles. Each mission and its constraints will be analyzed by the optimization method developed in this study for maximizing the utilization of electric power. A description of this method is included in later sections of this report. The specified missions are listed in Table IV.

Table IV. Selected Missions

	Mission I	Mission II	Mission III
Orbit	Synchronous equatorial	Sun synchronous	Elliptical, 31 deg inclined
Mission	Communications	Mapping, Navigation	Scientific experiments
Altitude	19,000 nmi	600 nmi	200 to 180,000 nmi
Life	5 years	1 - 3 years	1 year
Control system	Active 3- and/or 2- axis	As necessary	3-axis
Load power	150 - 500 w	150 - 500 w	300 w
Subsystem power inventory	Assigned by TRW	Assigned by TRW	Assigned by TRW

3.4 LOAD SELECTION

Space vehicle electrical loads are characteristic for a given vehicle and mission. For example, the electrical loads and duty cycles of a communications type satellite are predominately functions of the requirements ot the transmitters and receivers. The load data accumulated in Tasks I and II reveal that communications equipment requires a wide range of dc voltages (3 to 1500 v), with relatively close regulation. Significant amounts of power are required for each RF output stage depending upon the range, data rate, antenna gain, and output frequency. Multiples of this power can result if redundant equipment is used or if more transmitters are required for broader coverage of the frequency spectrum. Thus, it is possible to make some general observations about the characteristics of the electrical power system required to satisfy a given type of satellite mission. Specific power system requirements can only be defined when the vehicle design, mission constraints, subsystem inventory, ephemerides, and mission philosophy are enumerated.

The loads selected for the three specified missions (Table IV) were derived from existing satellite designs. The subsystem power requirements were increased to satisfy the specified total power by proportioning the increase among those subsystems primarily associated with the mission function. For the case of the communications mission, approximately 85 percent of the increase in power can be associated with the transmitters and receivers. The remaining 15-percent increase is associated with the housekeeping type subsystems.

Table V is a summary of the electrical load requirements for Mission III. The nominal total bus power is 300 w. This set of requirements will be used in the following sections to demonstrate the "optimization method" developed for this study. Maximizing system efficiency will be the criteria for this example.

Certain generalizations can be made about the method of maximizing power system efficiency from the parametric data. The following is a list of the more important rules bearing on load selection and grouping:

Table V. Mission III Load Power Requirements

Item No.	Voltage	Volt Amps/Watts	% Regulation	Frequency	Remarks	Voltage x Power	Percent of Total Power
1.	135 AC	302/100.7	+20, -15	400 cps	ø A	13,594.5	36.17
2.	125 AC	139/46.3	+20, -15	400 cps	ø B	5,787.5	16.63
3.	115 AC	15/8.0	±2.0	400 cps		920.0	2.87
4.	+ 70 DC	42.3	±2.0			296.1	15.19
5.	+ 28 DC	9.0	+20, -15			252.0	3.23
6.	28 AC	12/10.8	+20, -15	400 cps		302.4	3.88
7.	26 AC	6/2.0	+20, -15	400 cps		52.0	0.72
8.	+ 23 DC	5.8	±2.0			133.4	2.08
9.	+ 20 DC	7.0	±1.5		C.T. GRD	140.0	2.51
10.	- 20 DC	7.0	±1.5			140.0	2.51
11.	18 AC	3/1.6	±2.0	400 cps		28.8	0.57
12.	+ 16 DC	11.3	±1.0		C.T. GRD	186.2	4.06
13.	- 16 DC	0.4	±1.0			6.4	0.14
14.	+ 10 DC	0.5	±3.0			5.0	0.18
15.	+ 9 DC	21.1	±1.0			190.3	7.58
16.	- 6 DC	4.1	±1.0			24.7	1.47
17.	+ 5 DC	0.5	±1.0			2.5	0.18
		477/278.4					99.97

(1) Power requirements should be grouped in large blocks for processing by regulators, inverters, converters and/or transformer-rectifiers.

(2) Power conditioning and control equipment should be used only when necessary for any increment of power.

(3) Efficiencies of power conditioning and control equipment generally decrease in the following order for constant power outputs: TR units, inverters, regulators, and converters.

(4) Efficiencies of power conditioning and control equipment generally increase as power output increases, output voltage increases, voltage regulation percentage increases, number of output voltages decrease, the ratio of input/output voltage for regulators approaches unity, and as the input voltage regulation percentage decreases.

(5) Efficiency of the battery is only dependent upon state of charge, charge rate, discharge rate, charge temperature, and discharge temperature.

(6) Operating efficiency of the solar array is dependent only upon initial solar cell efficiency, illumination intensity, radiation history, temperature, and matched load impedance.

(7) The power required from the battery, especially that requiring conditioning, should be minimized.

These general guidelines suggest specific groupings of the load power requirements for any spacecraft. Table VI describes the results of the analysis of the Mission-III loads, and formed the basis for the recommended grouping. The process by which Table VI was developed is as follows:

(1) All output voltages were listed in descending order and numbered sequentially starting with 1. The sequential column is labeled A.

(2) Column B, adjacent to column A, was formed by assigning numbers according to the power output in descending order, starting with 1.

(3) The output power at each voltage (taken from Table V) was multiplied by that voltage. According to the descending order of magnitude of the product (P x V), numbers were assigned sequentially and listed in Column C.

Table VI. Load Power Requirements Organization

Item No.	Output Voltage	Voltage Rank	Power Rank	VxP Rank	$\sum$ A, B, C		Cumulative Percent of Total Power for A	Cumulative Percent of Total Power for B	Cumulative Percent of Total Power for C	Cumulative Percent of Total Power for D	Volt Reg Rank	Cumulative Percent of Total Power for AC Volts	Cumulative Percent of Total Power for DC Volts
		A	B	C	-	D	E	F	G	H	I	J	K
1.	135 AC	1	1	1	3	1	36.17	36.17	36.17	36.17	1	36.17	-
2.	125 AC	2	2	2	6	2	52.80	52.80	52.80	52.80	2	52.80	-
3.	115 AC	3	8	3	14	4	55.67	89.61	55.67	70.86	4	55.67	-
4.	+ 70 DC	4	3	5	12	3	70.86	67.99	74.74	67.99	6	-	15.19
5.	+ 28 DC	5	7	6	18	6	74.09	86.74	77.97	77.97	3	-	18.42
6.	28 AC	6	6	4	16	5	77.97	83.51	59.55	74.74	5	59.55	-
7.	26 AC	7	13	12	32	12	78.69	98.90	97.43	97.43	7	60.27	-
8.	+ 23 DC	8	11	11	30	11	80.77	96.71	96.71	96.71	8	-	20.50
9.	+ 20 DC	9	10	9	28	9	83.28	94.63	92.12	92.12	9	-	23.01
10.	- 20 DC	10	9	10	29	10	85.79	92.12	94.63	94.63	12	-	25.52
11.	18 AC	11	14	13	38	13	86.36	99.47	98.00	98.00	11	60.84	-
12.	+ 16 DC	12	5	8	25	7	90.42	79.63	89.61	82.03	13	-	29.58
13.	- 16 DC	13	17	15	45	15	90.56	99.97	99.61	99.61	14	-	29.72
14.	+ 10 DC	14	15	16	45	16	90.74	99.65	99.79	99.79	10	-	29.90
15.	+ 9 DC	15	4	7	26	8	98.32	75.57	85.55	89.61	15	-	37.48
16.	- 6 DC	16	12	14	42	14	99.79	98.18	99.47	99.79	16	-	38.95
17.	+ 5 DC	17	16	17	50	17	99.97	99.83	99.97	99.97	17	-	39.13

(4) The assigned numbers from columns A, B, and C were summed for each voltage and listed in the column labeled (Σ, A, B, C). Adjacent to this column, column D was formed by assigning numbers sequentially, starting with 1, according to the magnitude of the above sum (Σ, A, B, C) in ascending order (i. e., 1 represents the lowest sum).

(5) Column E, adjacent to column D, was formed by calculating in sequence the cumulative percentage of the total system power for each voltage listed. The sequence should parallel the order given in column A.

(6) Column F, adjacent to column E, was formed by calculating in sequence the cumulative percentage of the total system power for each power output. The sequence for calculating should parallel the numerical order given by column B, but is recorded opposite the correct voltage.

(7) Column G, adjacent to column F, was formed by calculating in sequence the cumulative percentage of the total system power for each output. The sequence for calculating should be in the numerical order given by column C, but recorded opposite the correct voltage.

(8) Column H was formed by again calculating the cumulative percentage of total system power but follows the numerical sequence given by column D.

(9) All output voltages were arranged in descending order of their percentage regulation. Within each group having the same regulation percentage the output voltages should be arranged in descending order of voltage. This list was numbered sequentially starting with 1 for the highest percentage regulation. Column I, adjacent to column H, was formed by listing the sequential number determined above opposite the correct voltage.

The sequence of column A reflects the preference for grouping the outputs according to the higher voltage. In column B, the sequence shows this preference according to power output. The voltage-power product preference of column C assists in the decision if columns A and B conflict. Column D normally would not be required, but it does provide additional information since it represents the sum of the preference factors. Because power has the larger influence on maximizing efficiency, it should be the primary consideration.

Since the first two voltages (135, 125 vac) represent 52.8 percent of the total power, they should obviously be conditioned by the same piece of equipment. An additional consideration, the fact that they are the components of a two-phase output, finalizes the decision. The third and fourth voltages (115 vac, 70 vdc) have the next highest preference, but the preference order is not clear cut between them. However, the third voltage is 400-cps ac and can easily be combined with the first two in the same equipment. The fourth voltage (+70 vdc) would require the addition of rectifiers and filters to this equipment if it were included, but it would significantly increase this equipment's portion (70.86 percent) of the total power. Alternately, if it is assumed that two pieces of conditioning equipment should be used with 135, 125, and 115 vac equipments comprising one package and with the +70 vdc incorporated in the second package along with the remainder of the voltages, two equipments would result, having approximately an equal percentage of the total power.

The decision is not clear cut; however, the "Comparative Analysis Optimization" part of this method (Section 3.6) permits a decision to be made between these two proposed designs on a relative basis.

The preference indicated by the degree of voltage regulation (column I) is not decisive. Columns J and K, which show the division of ac and dc power, indicate a possible third design configuration involving a regulated inverter and a regulated converter. Again, this proposed design can be compared on a relative basis with either of the previous two designs. In a similar manner, any number of alternate design configurations may be postulated. Each, in turn, can be evaluated against another configuration.

3.5 SYSTEM CONFIGURATION

The magnitude and trends established by the parametric design data have been shown to predominately influence the load division. Further, it is possible to formulate design optimization guidelines for each of the major equipments making up a power system design. Using these guidelines in conjunction with the mission constraints, an idealized design for each of the major equipments can be formulated. These ideal designs would establish the maximum individual performance capability for each equipment when used for the specified mission.

Figure 8 is an information flow diagram depicting the total optimization process. Starting from the left, the specified mission requirements and constraints are factored into the idealized equipment designs and power requirement organization (Tables V and VI). The Parametric Suboptimization Data provides the means for modifying the idealized design and minimizing the loss in performance. The integrated result is a set of Design Optimization Guidelines for each major equipment which allows the rational combination of these equipments into a power system.

Because the guidelines are not absolute, several desirable combinations may be synthesized. At this point, a technique such as the Comparative Analysis Optimization Method is required to evaluate the several system designs in light of the established optimization criteria. The Comparative Analysis Optimization process can be reiterated for as many proposed designs as necessary.

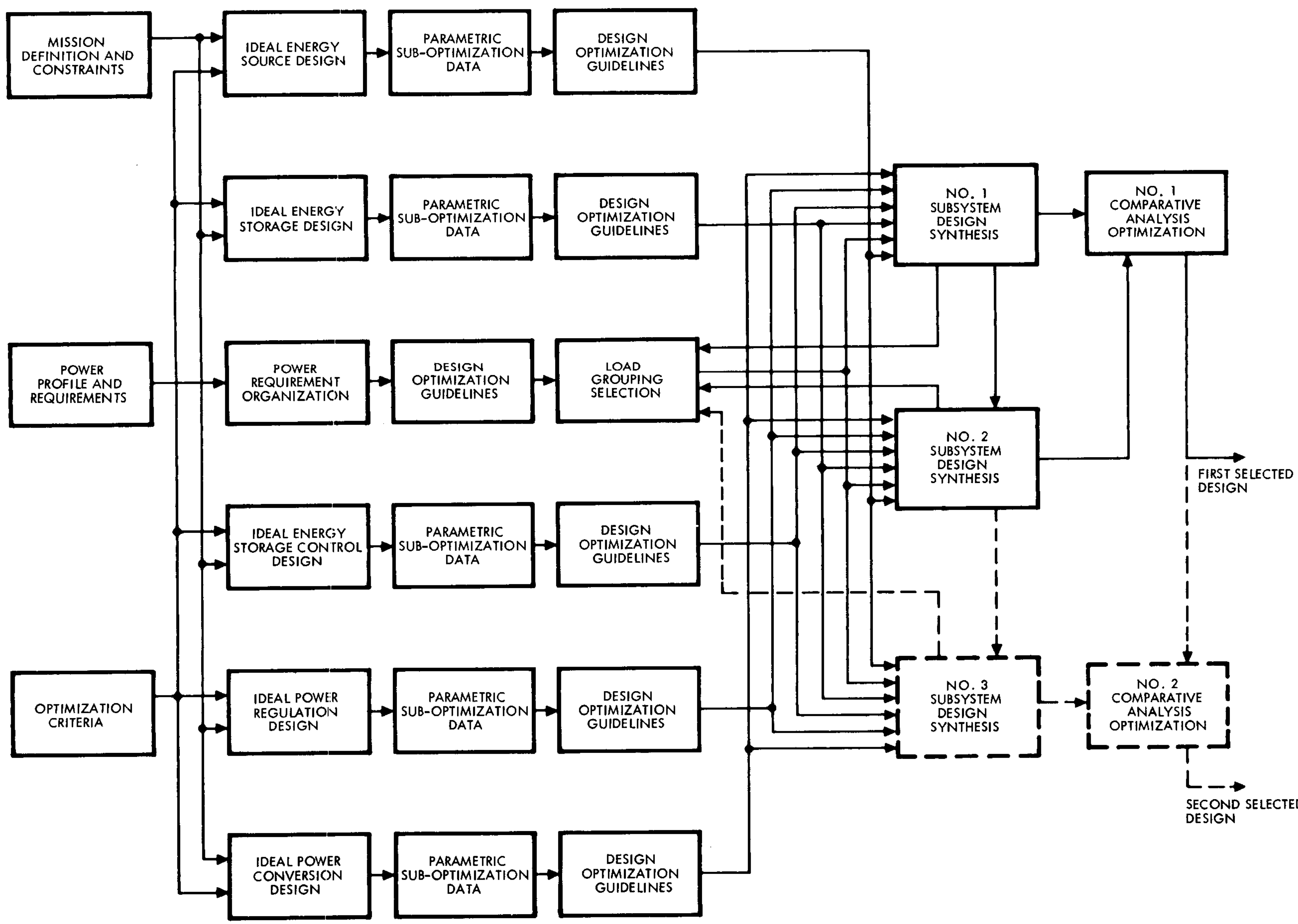

Figure 8. Optimization Flow Diagram

The generalized power system block diagram shown in Figure 9 represents all possible power system configurations. To fit a specific or proposed system into this diagram requires that efficiency (η) numbers representative of the system equipments be placed in the appropriate blocks. All other blocks not required in the proposed system are considered as 100 percent. The assigned efficiency numbers need only be accurate in a relative sense when two proposed designs are being evaluated by the Comparative Analysis Optimization Method.

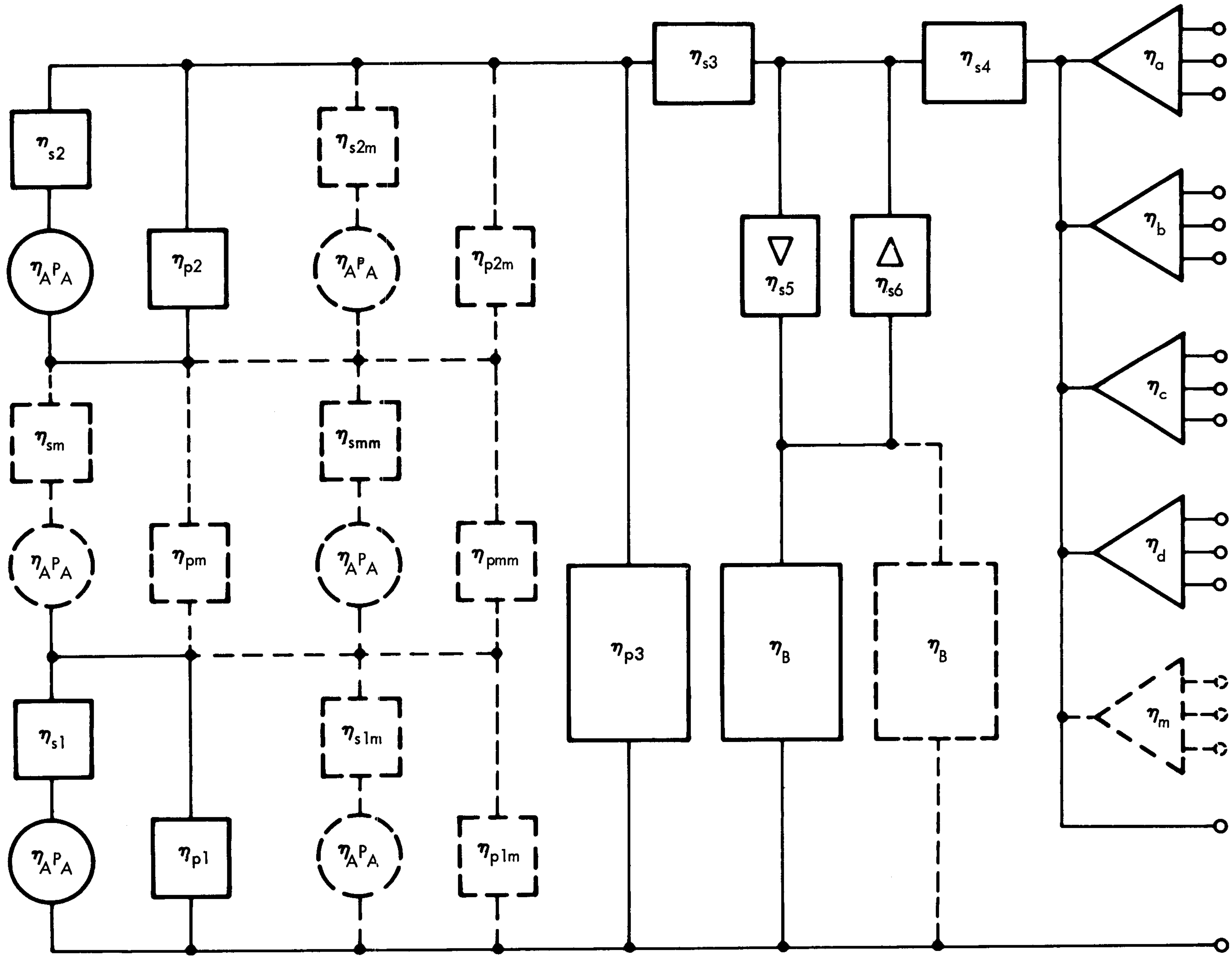

Figure 9. Generalized Power System Block Diagram

3.6 COMPARATIVE ANALYSIS OPTIMIZATION

Under a given set of conditions the total input power $\left(P_{in}\right)_1$ to the system from an energy source (see Figure 9) is

$$\left(P_{in}\right)_1 = \eta_A \sum P_A$$

where

P_A = maximum available power from the energy source element under optimum mission conditions

η_A = efficiency associated with the energy source for a given set of operating conditions.

Energy source controls can be either series or parallel in nature. The efficiency associated with these controls is designated by (η_s) or (η_p). From the regulated or controlled source the total input power (P_{in}) to the system is

$$P_{in} = \eta_A \eta_s \sum P_A \quad , \quad \text{or}$$

$$= \eta_A \eta_p \sum P_A$$

Similarly, the efficiencies associated with each piece of equipment can be multiplied by the input power to that equipment. The total power to the loads is then obtained by proper summation of the input power elements which have been decreased by their related efficiency factors. For the solar array—battery type system, the division of energy proportioned to the discharge—charge (dark to light) ratio must be considered. The total power to the loads can also be expressed as follows

$$P_{out} = \sum_{i=1}^{m} P_i = P_{out} \sum_{i=1}^{m} \Delta i \qquad (12)$$

where

P_i = the output power associated with each equipment just prior to the load

Δ_i = percent of the total power output associated with the equipment carrying the P_i amount of power.

The element of regulated source power associated with a P_i is:

During sunlight

$$P_{in} = \left[\sum_{i=1}^{m} \frac{P_i}{(\eta_{p3}\eta_{s3}\eta_{s4}\eta_i)}\right] + \left(P_{in}\right)_{dark} \tag{13}$$

where η_{p3}, η_{s3}, η_{s4} are the efficiencies related to the equipments conditioning the P_i power.

During dark

$$\left(P_{in}\right)_{dark} = \sum_{i=1}^{m} \frac{P_i\left(\frac{T}{t} - 1\right)}{(\eta_{p3}\eta_{s3}\eta_{s4}\eta_{s5}\eta_B\eta_{s6}\eta_i)} \tag{14}$$

During sunlight

$$P_{in} = \frac{1}{\eta_{p3}\eta_{s3}\eta_{s4}} \sum_{i=1}^{m} \left(\frac{P_i}{\eta_i}\right)\left[\frac{\left(\frac{T}{t} - 1\right)}{\eta_{s5}\eta_{s6}\eta_B} + 1\right] \tag{15}$$

where (T) is the total orbit time and (t) is the sunlight time of the orbit.

The total maximum available power from the energy source under optimum mission conditions is

$$\sum P_A = \frac{1}{\eta_A\eta_p^*\eta_{p3}\eta_{s3}\eta_{s4}} \sum_{i=1}^{m} \left(\frac{P_i}{\eta_i}\right)\left[\frac{\left(\frac{T}{t}\right) - 1}{\eta_{s5}\eta_{s6}\eta_B} + 1\right] \tag{16}$$

This equation can be separated into two parts, one related to the energy through the battery circuit and the other directly to the load.

Let

$$(\eta_A\eta_p\eta_{p3}\eta_{s3}\eta_{s4}) = \eta_c,$$

and

$$(\eta_{s5}\eta_{s6}\eta_B) = \eta_d$$

---

* η_s may be substituted for η_p depending on type of energy source control

then

$$\sum P_A = \left(\frac{1}{\eta_c} \sum_{i=1}^{m} \frac{P_i}{\eta_i}\right) + \left[\frac{1}{\eta_c \eta_d} \sum_{i=1}^{m} \frac{P_i\left(\frac{T}{t} - 1\right)}{\eta_i}\right] \tag{17}$$

Since $P_i = \Delta_i P_{out}$, $\quad P_{out} = P_i/\Delta_i$

$$\sum P_A = \left(\frac{P_{out}}{\eta_c}\right)\left\{\left(\sum_{i=1}^{m} \frac{\Delta_i}{\eta_i}\right) + \left[\frac{\left(\frac{T}{t} - 1\right)}{\eta_d} \sum_{i=1}^{m} \frac{\Delta_i}{\eta_i}\right]\right\} \tag{18}$$

The total power system efficiency (H) can be expressed as follows

$$H = \frac{P_{out}}{\sum P_A} = \frac{\eta_c}{\left(\sum_{i=1}^{m} \frac{\Delta_i}{\eta_i}\right) + \left[\frac{\left(\frac{T}{t} - 1\right)}{\eta_d} \sum_{i=1}^{m} \frac{\Delta_i}{\eta_i}\right]} \tag{19}$$

The total power system efficiency (H) can be maximized by

1) Increasing η_c, the power conditioning efficiency

2) Increasing η_d, the battery charge-discharge efficiency

3) Decreasing $\left[(T/t) - 1\right]$, the dark-to-light ratio

4) Decreasing

$$\sum_{i=1}^{m} \frac{1}{\eta_i},$$

the output stage efficiency of the power conditioning equipment

5) Increasing

$$\sum_{i=1}^{m} \eta_i,$$

equivalent to 4).

Therefore, for each proposed power system configuration, equipment efficiencies can be substituted into Equation (19). The resulting (H) for each configuration can then be compared in magnitude. The highest resulting number (closest to unity) will indicate the most efficient configuration.

Summary type equations can be written for other optimization parameters such as weight, reliability, etc. This Comparative Analysis Optimization method provides a relative ranking of the proposed configurations for any optimization criteria.